Commissioning of the APPLE II undulator

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Abstract

The source of the PETRA III soft X-ray beam line P04 (XUV beamline) is a so called APPLE II undulator[1], delivering radiation of tunable polarization. Its main operation modes (circular or linear horizontal polarization) exhibit very distinct spectral/spatial properties. For linear polarization, like in standard devices, all odd harmonics lye on axis, while in the circular mode all higher harmonics are off axis. Thermal and also radiation load on the optical components in the latter mode can thus be significantly reduced by a diaphragm, which can be positioned already within the accelerator shielding.

Preliminary commissioning of the beamline had to be made with optical components not yet designed to withstand the full thermal load of the linear mode but tolerating the load in the circular mode. From the point of view of radiation protection this would have led to an unsafe situation, because the computer control of the undulator is not part of the radiation safety interlock. Failure in this control could thus not only cause damage of the components, but also lead to an elevated radiation level. To nevertheless ensure radiation safety, a dose rate monitor acting on the beam shutter was installed in the optics enclosure. The radiation level outside the enclosure was then measured both in the circular mode and, with reduced current, in the linear mode. The radiation level, normalized to the current, inside the enclosure in the linear mode exceeded that in circular mode by six orders of magnitude. The threshold of the active dose rate monitor in the enclosure was than adjusted such that, in case of a failure in the undulator control leading to increases radiation, the beam shutter is closed assuring that there is never elevated radiation outside.

1. Introduction

1.1. PETRA III storage ring

PETRA III is the third reincarnation for the PETRA storage ring, which was built as an electron positron collider in the 1980s and became later a pre-accelerator for the proton electron collider HERA.
The conversion was carried out from the middle of 2007 till march 2009. 1/8 of the 2304 m long storage ring was completely rebuilt and houses now 14 undulator beamlines. The remaining 7/8 of PETRA have been modernized.

Parameter	PETRA III
Energy / GeV	6
Circumference / m	2304
Total current / mA	100
Number of bunches	960 / 40
Emittance (horz. / vert.) / nm	1 / 0.01
Number of insertion devices	14

Table 1 – Parameters of PETRA III

1.2. Undulators at PETRA III

PETRA III beamlines are supplied with light from different undulators depending on to the specific needs of the experiments.[2] Ten out of the 14 undulators are 2 m long planar devices with different period lengths (Fig. 1). The standard undulator (U29) is characterized by full energy tunability and a 1st harmonic position at 3.5 keV. Lower photon energies down to 2.4 keV are needed by certain X-ray spectroscopy techniques served by the spectroscopy undulator (U32) with a larger period length. A short period device (U23) is optimized for hard X-ray scattering experiments and provides tunability above the 3rd harmonic. In the long straight section before the new octant, a longer version of U32 (5+5 m) with 12.5 mm minimum gap is installed with the possibility to double the undulator length at a later stage.

This series of standard undulators is complemented by two specialized devices, one for the very hard X-ray regime, the other for XUV techniques. X-rays up to 300 keV as needed for the High Energy Materials Science Beamline will be provided by a 4 m long in-vacuum undulator (U19) having a period length of 19 mm. A minimum gap of 7 mm can be realized for the initial operation phase of the machine. This undulator will mainly be operated at high harmonics and is tunable above the 5th harmonic at 50 keV.
In collaboration with BESSY, an APPLEII undulator (UE65, 65.6 mm period length) was built for the Variable Polarization XUV Beamline at PETRA III. In the circular mode, it covers an energy range from 245 eV to 2.5 keV in the 1st harmonic and provides a high degree of polarization in the entire energy range.[3]

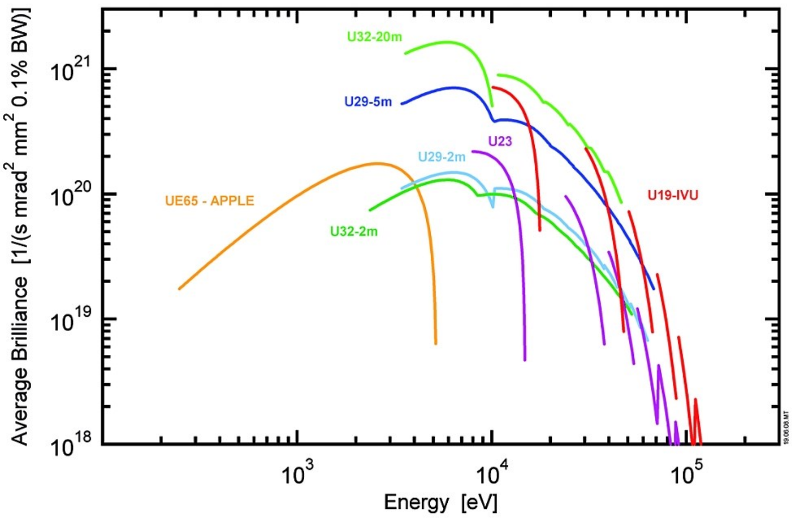

Fig.1 - Spectral characteristics of PETRA III undulators.

2. The APPLE undulator

APPLE stands for **A**dvanced **P**lanar **P**olarized **L**ight **E**mitter. It is made with 4 magnetic arrays that produce an oscillating magnetic field depending on the GAP between upper and lower arrays and on the longitudinal position of the opposite arrays. It is approximately 5 m long and has a period length of 65.6 mm. The minimum GAP is 11 mm. The desired polarization is selected by parallel or antiparallel shift of the longitudinally separated magnet rows. For zero shift the Apple provides linear horizontal polarization and resembles a usual planar pure magnet undulator with 1.1 T magnetic field. Moving longitudinally in parallel mode two arrays it is possible to change the magnetic field from horizontal to vertical. With a quarter wavelength shift the 1st harmonic provides 100% circular polarized radiation

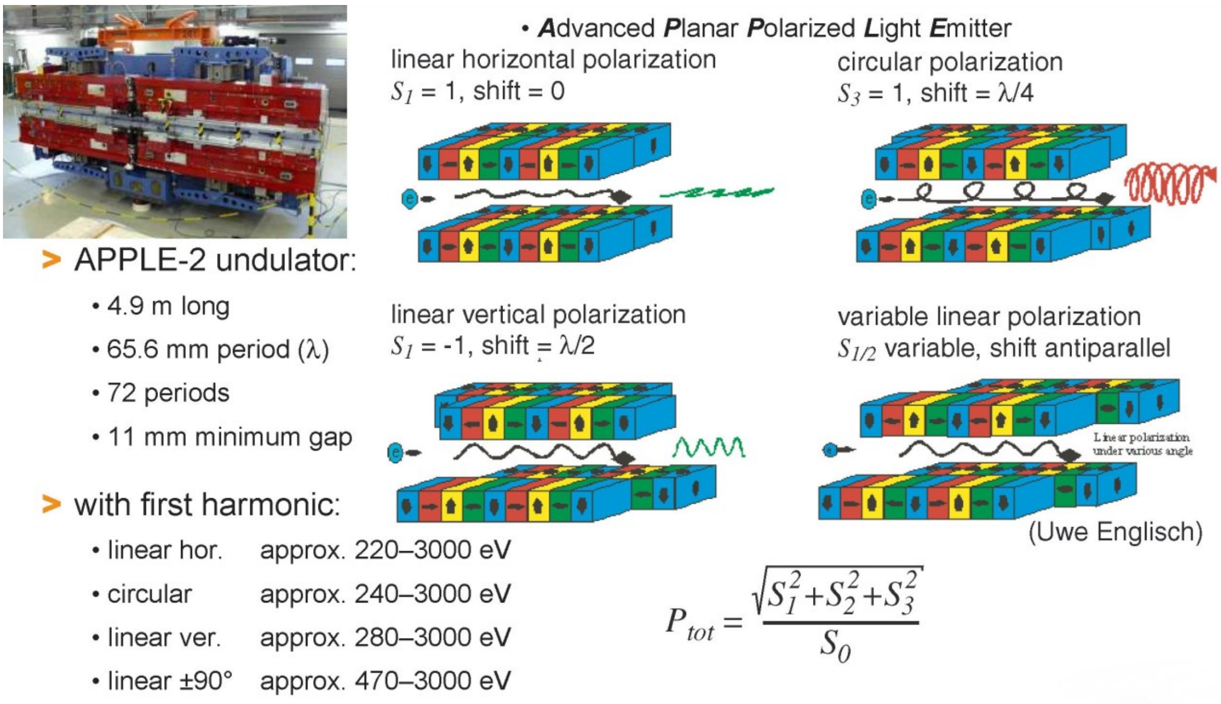

Fig.2 – magnetic arrays of the APPLE II undulators.

IDs on lower energy machines like BESSY, ELETTRA and ALS only produce circularly polarized light up to about 500 eV in the 1st harmonic. SLS and soleil will extend this limit to 700 – 900 eV. IDs at high energy machines like ESRF and Spring 8 can provide very high polarized light in the energy range of 500 – 2000 eV. At low energy storage rings energies above 900 eV can only be accessed by higher harmonics which do not exhibit full circular polarization .The figure 3 compares the flux in the different operation modes for different accelerators at 100 mA.
Soft x-rays are ideal for spectroscopic investigations ranging from magnetism in nano-structures to biological systems. The APPLE undulator generates 100% horizontal and circular polarized light in the 1st harmonic over the full energy range of the beamline. Many absorption edges lie in the soft x-ray range from 100 eV to 3 keV. The energy range of this APPLE undulator has been specified by users to reach from 250 eV to 3 keV. The lowest photon energy of 160 eV can be reached only in the horizontal linear polarized mode. The onset of the 1st harmonic depends on the magnetic field (GAP). The variable polarization soft x-ray beamline is providing the highest brilliance and flux in the important spectral region from 500 eV to 2,5 keV with a flux more than 10 to the 12 ph/s.

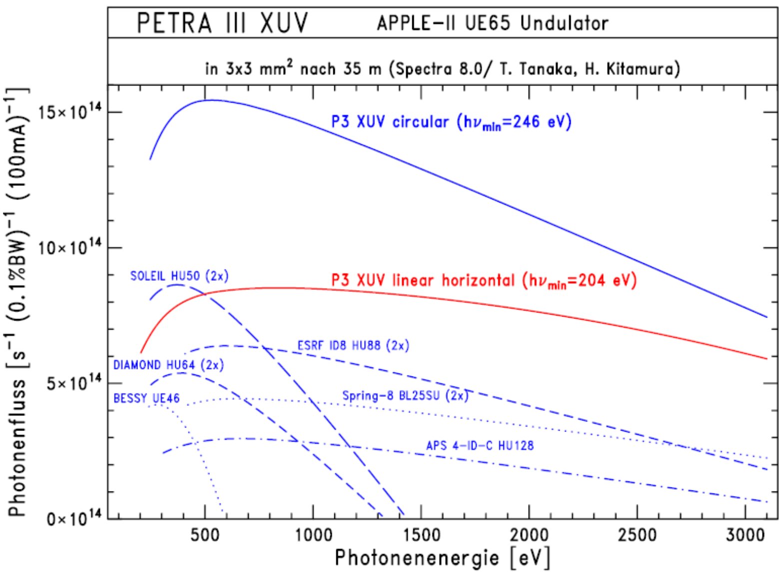

Fig.3 - characteristics of the APPLE II undulators.

3. Design of the P04 XUV beamline

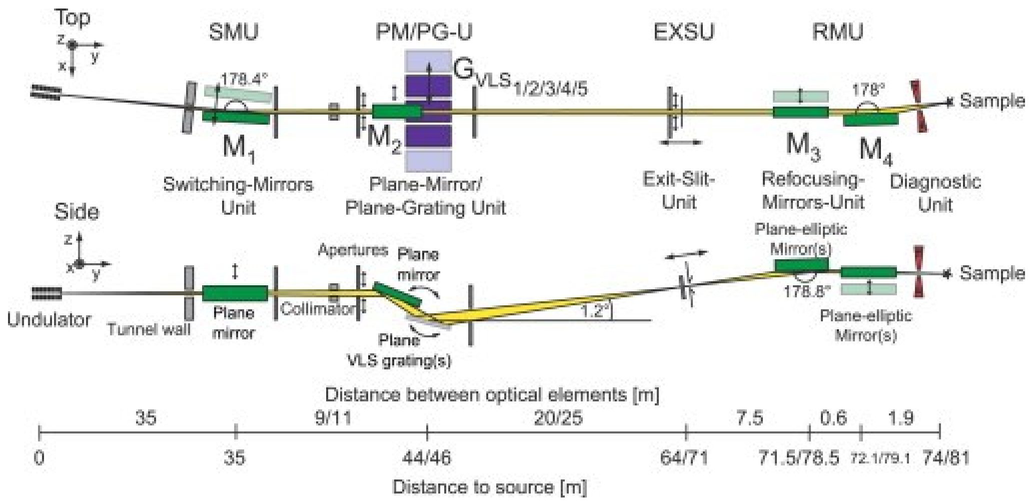

Fig.4 – P04 XUv beamline

The P04 XUV beamline is up to now not in the final upgrade status.
The Mirror M_1 is situated inside the switching mirrors unit (SMU) which allows to serve two branch lines of the beamline P04 enabling a fast switching between two independent experiments. Each branch may be adapted to the specific needs of different experiments. Mirror M_1 has to withstand a rather high power of up to 1.5 kW (at 100 mA storage ring current). Power (density and FEM-calculations showed, that only internal liquid nitrogen cooling keeps the deformations due to the heat load within acceptable limits. In contrast to this, FEM-analysis indicated that internal water cooling is sufficient for mirror M_2 which is the pre-mirror in front of the grating and is expected to absorb more than one order of magnitude less power (up to 48 W at 100 mA). The focusing onto the exit slit is performed by a varied line-space (VLS) plane grating. Due to the long exit arm length only a modest variation of the line density is required.

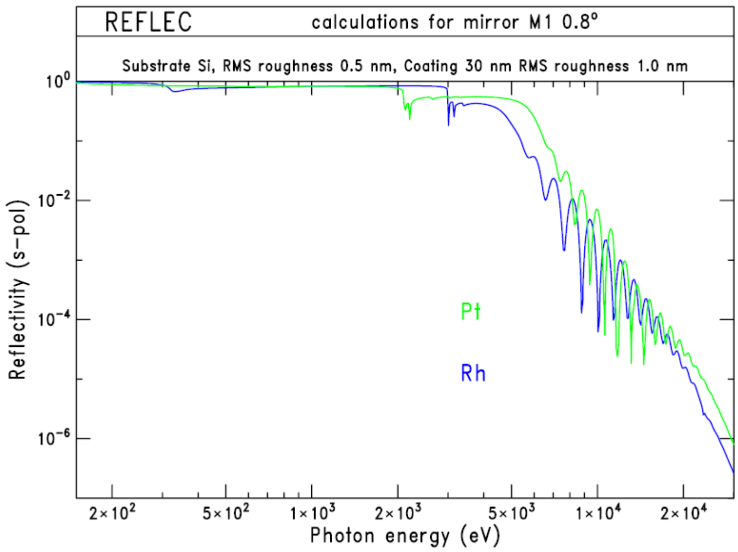

Fig.5– Reflectivity of mirror M1 for different coatings

For radiation safety aspects it is only interesting what happens inside the optics hutch. The SMU cuts off energies above 3 keV depending on the coating. After the optics hutch there is no further shielding except the beam tube.

4. Fixed aperture ES XL P04

4.1 Requirements for the fixed aperture

To reduce the power density and the heat load on the SMU a fixed aperture is installed in the front end. The requirements for this aperture were:

- Off-axis option for the single beam
- Absorption of the dipole- and undulator radiation in front of the vertical slit system except for an exit diameter of 4 mm, 17 m away from the source
- Water-cooled aperture
- Absorption of the scattered radiation by densimet shielding
- Temperatur control

4.2 Heat loads of the fixed aperture

The APPLE Undulator has 3 modes:
<u>Total power on the water-cooled fixed aperture:</u>
Linear horizontal = 13.7 kW
Linear vertical = 10.3 kW } 100 mA, closed GAP (11 mm)
Circular = 12.1 kW

<u>Behind the water-cooled fixed aperture:</u>
Linear horizontal = 3.1 kW
Linear vertical = 2.6 kW } 100 mA, closed GAP (11 mm)
Circular = 12 W

The ring-shaped power density of the higher harmonics is totally absorbed in the circular mode. Figures 6 – 8 shows the power density for the three different polarizations without and with the fixed aperture for 100 mA and closed GAP. The maximum power density for the circular mode (named the higher harmonics) is located off-axis in a donut shaped ring. This ring is outside the 4 mm diameter of the aperture. The 100% circular polarized first harmonic in the centre can pass the aperture.

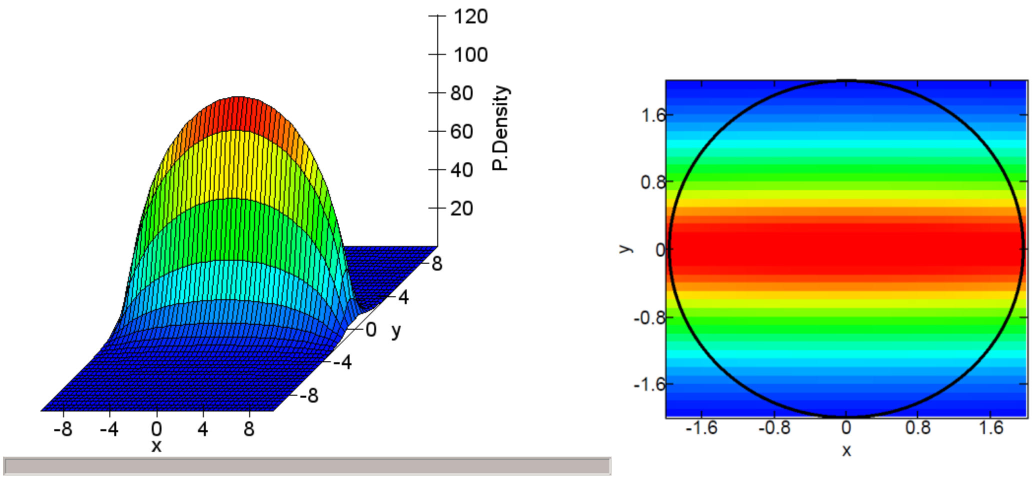

Figure 6: vertical polarization at 17 m

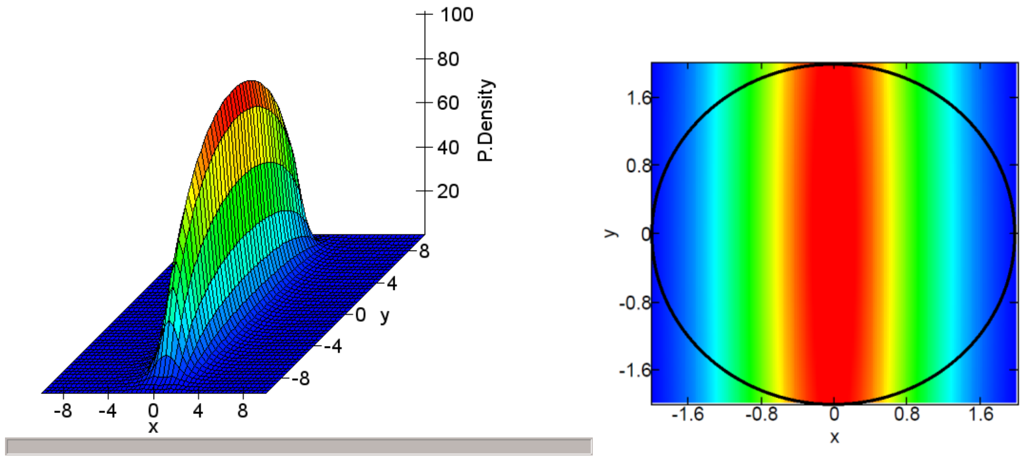

Figure 7: horizontal polarization at 17 m

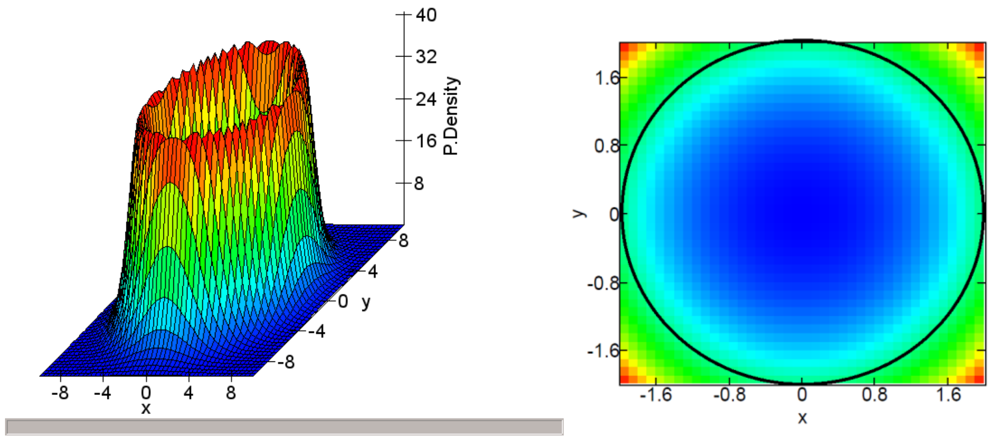

Figure 8: circular polarization at 17 m

Figures 9 and 10 shows the Photon flux through and on the aperture for linear and circular polarization for 100mA and closed GAP. In the circular mode no higher harmonics above 3 keV can pass the aperture. In the linear mode it becomes obvious that with higher energies the ratio of the flux through the aperture increases and approximates to the flux which is blocked by the aperture because all odd harmonics lye on axis.

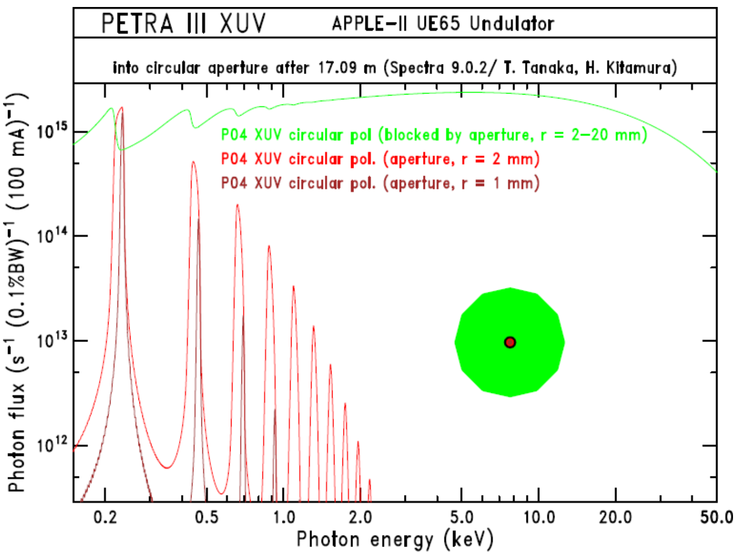

Figure 9: Photon flux into aperture for circular polarization

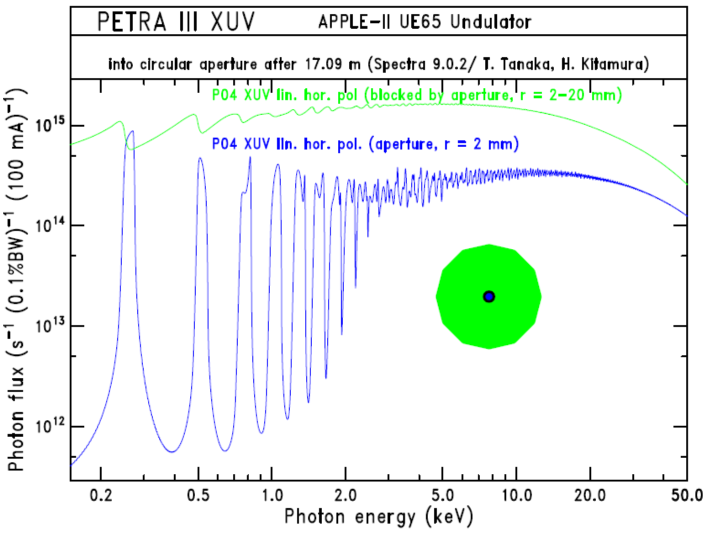

Figure 10: Photon flux into aperture for linear polarization

5. Shielding calculations for the optics hutches at PETRA III

The PETRA III experimental hall is a non-controlled area, so the dose limit is set to 1 mSv/a. That is corresponding to 0.5 µSv/h for 2000 working hours during a year. A loss of the primary electron beam is excluded. Behind each undulator is a deflecting magnet which separates the charged electrons of the beam from the unloaded synchrotron radiation and bremsstrahlung. In addition there is a permanent magnet which directs the electrons inside the ring tunnel on the beam tube wall in case the separation magnet is without current. The optic hutch must shield scattered bremsstrahlung, neutrons and synchrotron radiation. Interactions of the bremsstrahlung with the optical components of the beamline generates low energy neutrons. Only bremsstrahlung produced in the straight section can travel along the beamline. The gasbremsstrahlung interacts with the atoms of the residual gas inside the vacuum beamtube. The dose rate by the bremsstrahlung and neutrons and the required shieling is calculated with FLUKA with the following parameters:

	Symbol	FLUKA	Few-Bunch	Multi-Bunch
Electron energy	E	6 GeV	6 GeV	6GeV
Running time	T	6000 h	6000 h	6000 h
Beam current	I	7.4 pA	100 mA	200 mA
Length undulator section	L	6.5m	14.5 m	14.5 m
Pressure	p	100000 Pa	3,3 µPa	1,7 µPa

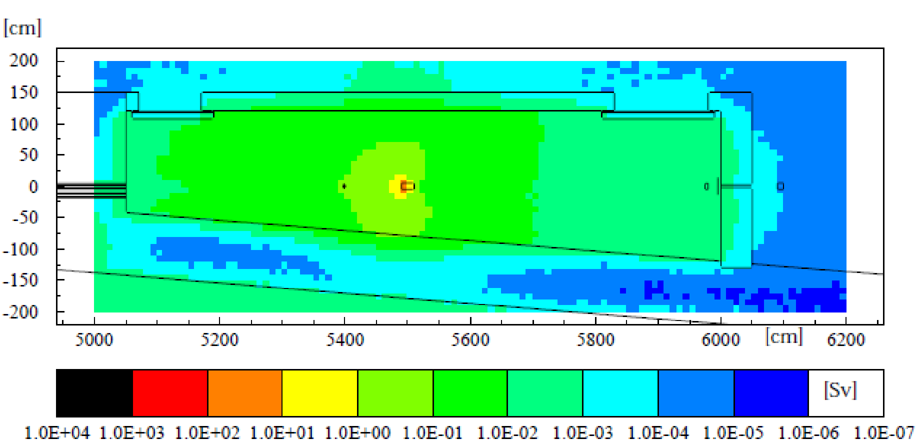

Figure 11: equivalent dose caused by neutrons with 1200 Ah and 1,7µPa air in the undulator section

The calculations for the synchrotron radiation were done for silicon and copper target of 1 cm thickness and 1 cm radius. It was assumed that the scatterer is 1m away from the outside walls. The dose also depends on the scattering angle from the synchrotron radiation beam axis.

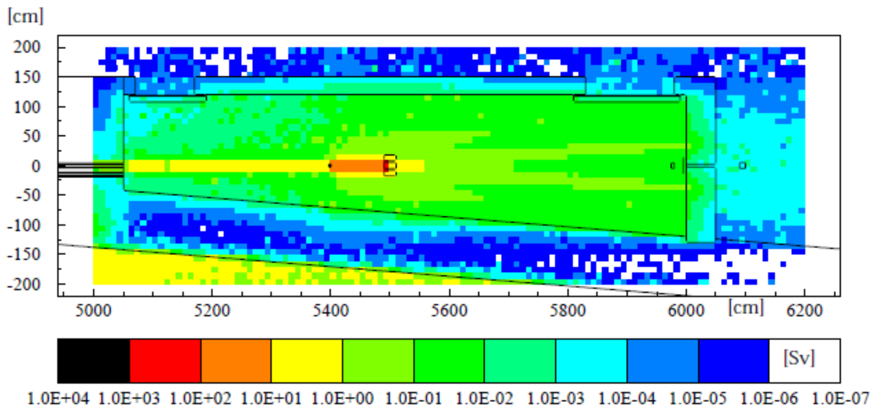

Figure 12: equivalent dose caused by electro- magnetic radiation with 1200 Ah and 1,7µPa air in the undulator section

The calculations for the bremsstrahlung and synchrotron radiation results in a 30 cm thick side wall and roof and a 50 cm back wall. Heavy concrete is an economic compromise between low Z material against neutrons and high Z material against scattered electromagnetic radiation. The planning goal of 3 mSv per year was reached for 13 out of 14 optic hutches on all position. Only the APPLE undulator causes higher annual doses. The calculations were made without the fixed aperture in the front end. The APPLE undulator is designed to get with the first harmonic into the soft x-ray region. Due to the higher magnet field and higher K value of the undulator, higher harmonics are on axis in the linear mode. Because there was only one type of this optic hutch it was decided to have local shieling inside the hutch in the future if necessary. Preliminary commissioning of the beam line had to be made with optical components not yet designed to withstand the full thermal load of the linear mode but tolerating the load in the circular mode. From the point of view of radiation protection this would have led to an unsafe situation, because the computer control of the undulator is not part of the radiation safety interlock. Failure in this control could not only cause damage of the components, but also lead to an increased radiation level.

Position	Bremsstrahlung		Synchrotronradiation		total
	Gamma	Neutrons	Spec-U	Apple-U	
D1	0,1 mSv	0,6 mSv	0,00004 mSv	0,00005 mSv	1,6 mSv
S1	0,3 mSv	1,6 mSv	0,1 mSv	1,9 mSv	2,0 mSv
D2	1,0 mSv	0,3 mSv	0,2 mSv	6,0 mSv	1,5 mSv
B1	2,2 mSv	0,2 mSv	0,8 mSv	15,6 mSv	3,2 mSv
Goal					3 mSv

Table 1: Results for the shielding calculations

6. Radiation measurements at P04

It was part of the “old DORIS philosophy” to have local shielding and an observation inside the hutch. At PETRA III all shieldings are calculated in a sufficient thickness without any local shielding, except the optics hutch of P04. To ensure radiation safety, a dose rate monitor acting on the beamshutter was installed inside and outside the optics hutch, next to the SMU. The radiation level outside and inside the enclosure was measured both in circular mode and, with reduced current, in linear mode. In the linear mode we measured

7.8 mSv/h next to the SMU for 1 mA and 13 mm GAP. In the circular mode we measured 0.11 μSv/h in average next to the SMU for 100 mA and 13 mm GAP. Outside we measured for circular polarization a dose less than 0.2 μSv/h. In the linear mode we measured on 2 positions a dose of 0.3 μSv/h. To be sure that we do not have a radiation level above 0.5 μSv/h we set the threshold of the dose rate monitor to 19 mSv/h inside the hutch. In case of a failure in the undulator control that causes an increase of radiation, the beam shutter is closed to make sure that there is never elevated radiation outside.

7. Conclusions

In about a year the new SMU with liquid nitrogen cooling will be installed. Further radiation measurements will be required. When necessary local shieldings must be installed next to the SMU. Free space is foreseen in the design of the SMU for some local shielding. Probably some additional beam tube shieling will be required in the back wall. Other possible weak spots in the shieling may be the sliding door and lead through in the side walls.

References

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